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Abstract: In recent years there has been an upsurge of studies on ecosystem multifunctionality (EMF), or the ability of ecosystems to simultaneously provide multiple functions and/or services. The concept of EMF itself, the analytical approaches used to calculate it, and its implications depending on the spatial scale and field of study have been discussed in detail. However, to date there has been little dialogue concerning the basis of EMF studies: what should or should not be considered appropriate measures for ecosystem functions. To begin this discussion, we performed an in-depth review of EMF studies across four major terrestrial ecosystems (agroecosystems, drylands, forests and grasslands) by analysing 82 studies, which together have assessed 775 ecosystem functions from a variety of field and greenhouse experiments across the globe. The number of ecosystem functions analysed varied from two to 82 per study and we found large differences in the distribution of functions across ecosystem types and ecosystem service categories. Furthermore, there was little explanation of why certain variables were included in the EMF calculation or how they relate to ecosystem functioning. Synthesis. Based on the literature analysis, it is clear that there is no general agreement regarding which measurements should or should not be considered functions in the field of ecology. To address this issue, we propose a general guideline for determining and measuring appropriate functions.

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A closer look at the functions behind ecosystem multifunctionality: A review.

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Data accessibility statement: All original papers included in the literature review are cited in the references list (Table S1). Data associated with this article can be found in Figshare (DOI:10.6084/m9.figshare.12624680).

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Abstract

In recent years there has been an upsurge of studies on ecosystem multifunctionality (EMF), or the ability of ecosystems to simultaneously provide multiple functions and/or services. The concept of EMF itself, the analytical approaches used to calculate it, and its implications depending on the spatial scale and field of study have been discussed in detail. However, to date, there has been little dialogue concerning the basis of EMF studies- the functions themselves- nor what appropriate measures for ecosystem functions are. To begin this discussion, we performed an in-depth review of EMF studies across four major terrestrial ecosystems (agroecosystems, drylands, forests, and grasslands) by analysing 82 studies, which together have assessed 775 ecosystem functions from a variety of field and greenhouse experiments across the globe. The number of ecosystem functions analysed varied from two to 82 per study and we found large differences in the distribution of functions across ecosystem types. Furthermore, there was little explanation of why certain variables were included in the EMF calculation or how they relate to ecosystem functioning. Based on the literature analysis, we propose a general guideline for determining and measuring appropriate functions.

Introduction

The multiple threats posed by climate and land-use change, such as more frequent droughts, mega-fires, and loss of biodiversity (Costello *et al*. 2009; Bellard *et al*. 2012), have put a clear priority on the importance of maintaining our environment, while at the same time providing enough food, fuel and fibre to support the burgeoning population (United Nations 2015). Yet measuring and weighing trade-offs between different aspects of ecosystem services and functions is a complex and challenging task. Researchers and policy makers have attempted to accomplish this task using the well-known concept of ecosystem services, or the benefits provided to humans from ecosystem functions (Costanza *et al*. 1997; Fig. 1). This effort has led to influential reports and frameworks that have shaped environmental policy for decades (MEA 2005; Gómez-Baggethun *et al*. 2010; United Nations 2015). Although several different frameworks for conceptualizing and categorizing these functions and services exist (MEA 2005; Díaz et al., 2015; Díaz et al., 2018; TEEB, 2018), the majority are generally discussed in the framework of cultural, provisioning, regulating, and supporting ecosystem service categories (Fig. 1).

One of the key approaches to measure and appropriately manage ecosystems is to gain an understanding of how these functions and services are measured. In recent years, a relatively new practice to fulfil this goal has emerged in which researchers have begun to calculate a single measure to characterize the "overall functioning of an ecosystem" (Hector & Bagchi 2007; Gamfeldt et al., 2008) or the "ability of ecosystems to simultaneously provide multiple functions and services" (Manning *et al*. 2018) in a term commonly referred to as ecosystem multifunctionality (EMF). Here we define ecosystem functions as the biotic and abiotic processes that occur within an ecosystem and may contribute to ecosystem services either directly or indirectly (Fig. 1). While previous studies on key drivers of ecosystem functioning tended to assess single functions, more recent studies have focused on understanding the drivers of multiple ecosystem functions simultaneously (Maestre *et al*. 2012; Wagg *et al*. 2014; Lefcheck *et al*. 2015). This was an important progression for ecological research, since measuring only one ecosystem function does not consider the trade-offs between ecosystem functions, nor how changes in factors such as biodiversity and land management practices would affect these multiple functions overall (Allen et al., 2015).

The focus on EMF has brought new perspectives on the importance of biodiversity for ecosystem functioning (Meyer *et al*. 2018; Schuldt *et al.* 2018) and the impacts of global change drivers such as increases in temperature or the impact of wetting-drying cycles (Delgado-Baquerizo *et al*. 2017), to name a few. However, it has been much more challenging to transform the idea of EMF into a useful assessment tool for scientists and policy makers (Manning *et al*. 2018). In fact, the validity of the multifunctionality concept has been thoroughly debated in recent years (Bradford *et al*. 2014a,b; Manning *et al*. 2018; Table 1). Yet the main focus on EMF so far has been centered around the methodology and number of individual functions used to calculate it (Byrnes *et al*. 2014; Lefcheck *et al*. 2015; Gamfeldt & Rogers 2017; Meyer *et al*. 2018; Jing et al., 2020). In contrast, there is very little consideration of how the reported functions contribute to the overall ecosystem functioning or the provisioning of ecosystem services, and how the inclusion or exclusion of particular functions, in contrast to the number of functions (Allan *et al*. 2015; Gamfeldt & Rogers 2017; Meyer *et al*. 2018), affects the overall assessment of EMF. Moreover, in the EMF literature it is common to see ecosystem properties (i.e. soil pH, soil depth, water content, etc.), reported as functions, instead of drivers or regulators of such functions (Table S1). It is likely that these parameters are included in EMF calculations due to confusion amongst researchers regarding what an ecosystem function is and what an appropriate indicator of such functioning can be. Here we define indicator as a component or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions, as proposed by Heink and Kowarik (2010) (Fig. 1). For example, in a review linking soil functioning with ecosystem service provision, Bünemann *et al.* (2018) found that the word 'function' was used interchangeably as a process, function*ing*, role, and service. As a result, it is difficult to instinctively understand what is included in such an assessment, and how the term EMF actually relates to the overall functioning of an ecosystem.

Recent work has deepened our insights into the definition and development of EMF (Manning et al. 2018), its application to global change research (Gilling *et al*. 2018), and its differences in conceptualization across research fields (i.e. ecosystem multifunctionality compared to landscape multifunctionality) (Hölting *et al*., 2019). However, while Hölting et al. (2019) analysed 101 studies on the functions used across both ecosystem multifunctionality and landscape multifunctionality studies together, whether or not the specific functions or indicators were appropriate for such an assessment was not discussed. We propose that such an assessment is not only lacking, but also particularly necessary for several reasons. First, the value, robustness and strength of EMF assessments depends primarily on the functions used to calculate it. Second, a review of functions in the EMF literature can show us what types of functions have received the most attention in recent and past studies, how these differ between ecosystem types under study, and thus where research gaps remain. Lastly, it is important to reflect on whether or not the variables reported as functions in EMF assessments are indicative of actual functions. To address these aforementioned issues, we performed a literature review of EMF studies to analyse which functions are used to calculate EMF across four major ecosystem types (agroecosystems, drylands, forests, and grasslands). We then use these results to discuss how well the reported functions or indicators are linked to ecosystem functioning and service provision, as well as give recommendations for how to choose appropriate functions in order reduce ambiguity in the term EMF.

Literature review

We conducted a literature search on 1 July 2018 which included all peer-reviewed publications in the Web of Science database published before this date. We conducted this review by first searching for 'multifunctionality' in the Web of Science database and refined by the research areas: ecology, environmental sciences, microbiology, environmental studies, biology, geography, agriculture multidisciplinary, soil science, multidisciplinary sciences, agronomy, plant sciences, agricultural economics policy, forestry, biodiversity conservation, and agricultural engineering. We then removed all publications that were listed twice, which resulted in a total of 1,029 references. Many of them were related to landscape management or multifunctional agriculture, which did not calculate a multifunctionality index using measured ecosystem functions, but instead discussed the impact of different landscapes or cropping systems on a variety of socio-economic and political issues, and therefore were beyond the scope of our study (e.g. see Hölting *et al*. (2019) where landscape multifunctionality is discussed). We then narrowed the search terms to 'multifunctionality and ecosystem' of terrestrial ecosystems, refined the search by the same research areas as stated above, and removed all duplicate publications, which resulted in a final list of 268 papers (Fig. S1).

We divided these 268 papers into those that: a) calculate EMF, b) measure a number of individual functions and discuss the overall results in terms of EMF, but do not calculate a final EMF value (i.e. mapping regions with more or less of a given number of functions), c) discuss EMF but do not measure it directly (i.e. reviews and discussion papers), and d) do not measure multiple functions, calculate an ecosystem EMF value, nor discuss it in detail. From this final list, 32%, or 86 papers, were redistributed to different individuals within the group of authors, who then applied the same search criteria and grouping categorizations. This was done as a quality assurance measure to make sure that all papers were being categorized similarly even when screened by different people, according to the protocol of Meissle *et al.* (2014). All papers were grouped into the same categories during this cross-check phase, thus supporting our categorization criteria. Following the cross-check, we then chose all papers from categories a) and b) for further analyses since these measured multiple ecosystem functions and discussed them within the framework of EMF. Papers categorized into the final two categories (i.e. c and d, totalling 186 papers) were removed from our list. Using the data from categories a) and b), we compiled a table including information on the ecosystem type, number and type functions measured, and the methodology used to calculate EMF. The final list had a total of 82 papers, over half of which have been published since 2016, thus highlighting the steep increase in EMF studies in recent years (Fig. 2). From this final list of paper, we then compiled a table including information on the ecosystem type, number and type functions measured, and the methodology used to calculate EMF (see complete list in Table S1).

Are ecosystem functions necessarily linked with ecosystem service provision?

To effectively guide the advancement of research in the field of EMF, it is essential to understand a) if the various functions measured in EMF literature are currently being linked to ecosystem services, either directly or indirectly, and b) if so, how this is done. Although it is well-accepted that most biodiversity-ecosystem-functioning studies are assessed mainly from an ecological perspective (i.e. without human valuation) (i.e. Fig. 1b), we found still that many studies in our review discussed how certain measured functions contribute to ecosystem service provision (Fig. 1a). Therefore, we began by compiling a list of how each paper classified the measured functions according to the service it contributes to (Table 2). For those papers that specified why they chose to measure certain functions (i.e. see Maestre *et al*. 2012; Fanin *et al*. 2018), we found that some chose to assess functions across a wide range of ecosystem service categories (Schipanski *et al*. 2014; Allan *et al*. 2015), while others chose to look not at overall ecosystem functioning, but instead at specific aspects of functioning such as the role of different parameters on C, N and P cycling and/or storage (Lohbeck *et al*. 2016; Eldridge *et al*. 2016; Luo *et al*. 2017), or wild food production (Granath *et al*. 2018). Still others never explicitly state which functions were actually measured, but only discuss the final value of EMF without discussing the functions they considered (Lefcheck *et al*. 2015, Meyer *et al*. 2018). Given the large range of potential functions included in such studies, we feel that it is imperative that future studies make it clear which functions were included in their analysis and why, so that readers can appropriately interpret the overall EMF index within the context of each specific study.

Since direct information linking the measured functions with service provision was not available for all reviewed studies, we classified each of the measured functions into one of 24 functional categories dispersed among the four major ecosystem service categories identified by the Millennium Ecosystem Assessment (MEA 2005) (cultural, provisioning, regulating and supporting, Table 2). This was done not only to condense an otherwise unmanageably long list of individual functions (775 in total), but also to gain insight into how evenly the major ecosystem service categories are being represented in EMF literature. We believe that this classification scheme was an appropriate fit for the published functions, meaning that each ecosystem service was represented within the literature, and each published function could easily fit within one of these services. The decision of which ecosystem service category to place the functions was agreed upon by all co-authors during lengthy discussions in which the primary role of each individual function was discussed within the context of our definition of ecosystem function (i.e. as suggested by Jax, 2005). However, while we were able to place each published function in a single category, it is clear that in many cases a given function could potentially contribute to multiple functions or ecosystem services, which has been discussed previously (Constanza *et al*. 1997; Giling *et al*. 2018; Nilsson et al. 2017).

Distribution of functions across ecosystem types

In our assessment, we found that 30% of the papers were from grasslands, 23% from forests, 16% were from drylands, and 27% from agricultural systems (Table 3). These four main ecosystem types were not subdivided further (i.e. natural versus managed grasslands or primary versus secondary forests) because this type of ancillary information was not available for most studies. However, these broad categories are still useful for analysing differences in EMF assessment between major ecosystem types. For example, using these categories we were able to compare our results with the distribution of global land use types to get an idea of how well our focus on EMF aligns with global averages (Fig. 3). Overall, grassland and forest ecosystems were relatively evenly represented in relation to their global distribution (30% and 23% in EMF studies compared to 23% and 26% in global distribution, respectively). However, agricultural systems and drylands were over-represented, while the barren land and glaciers were under-represented compared to their global distribution.

In addition, there was also discontinuity between ecosystem categorizations. For example most studies were grouped by land-use type (i.e. grassland, forests, etc.) while others were grouped by environmental zones such as “drylands” (Maestre *et al*. 2012; Delgado-Baquerizo *et al*. 2016) or “peatlands” (Robroek *et al*. 2017). Most studies were conducted in a field setting, others were assessed using a greenhouse or soil incubation approach, and a minority did a meta-analysis of EMF studies investigating the role of a variety of modifying factors of EMF, such as differences in trophic levels (Lefcheck *et al*. 2015). Additionally, most of these studies assessed EMF at only one time point, while only one experimental study assessed how plant species diversity impacts EMF over several years (Meyer *et al*. 2018) (Table S1). Within each ecosystem type, the average number of functions per study varied between 5.6 and 10.6, showing great similarity to the median values (between 5 and 9) (Table 3). However, across all ecosystem types, the number of functions assessed per study ranged between 2 and 82, thus highlighting the wide variety between studies (Table 3). Our study complements the findings of Hölting et al. (2019) who found an average of 8 functions and services per study, although only 47% of the studies reviewed here overlapped with this study (Table S1).

We found that there was a difference in the distribution of functions between ecosystem types (Table S2; Fig. 4). For example, studies conducted in drylands measured functions falling exclusively in the 'supporting' and 'regulating' ecosystem service categories, with 86% of measured functions falling within the 'supporting' category. In contrast, functions measured within the agricultural and forest ecosystems were much more evenly distributed across the four ecosystem service categories. Yet despite these general differences across ecosystem types, we found that the range of functions often differed greatly between studies of the same ecosystem type as well. For example, even within a forest ecosystem, some studies measured only 'supporting' functions (Bastida *et al*. 2016; Eldridge *et al*. 2016), others measured only 'provisioning' functions (Granath *et al*. 2018), and still others measured a relatively even distribution of all ecosystem service categories (van der Plas *et al*. 2016a,b). While some of these differences may be due to the success of certain research groups in publishing studies in a specific ecosystem type (i.e. drylands in the Maestre group), it is clear that the concept of EMF is in practice very ambiguous if different studies include such a range of functions. This requires the reader to carefully consider the particular functions included in the analysis to understand 1) the extent of multifunctionality that was in fact explored and 2) the constraints imposed to generalizations on EMF from each study design.

Measuring ecosystem functions

In addition to discussing which functions are being measured and whether or not they are linked with ecosystem services, one issue which must be addressed is the variability in how functions are being assessed (i.e. either by direct measurement or by the measurement of indicators) (Fig. 1). In contrast to reported ecosystem services, which were more straightforward to measure and require human valuation (i.e. via surveys or direct inventories), our review found that the line between an ecosystem function and an indicator of an ecosystem function was often unclear how a given measure was related to an ecosystem function. For example, we found that in addition to well-accepted ecosystem functions (i.e. rates of N_2O production, biomass production, etc.), in many cases several variables that do not reflect functions, including soil pH, soil water content, soil depth, soil slope, and cation exchange capacity were included in the EMF calculation as well (Table S1). From our perspective, these latter variables are neither ecosystem functions nor appropriate indicators of functions, but are instead a collection of inherent soil physicochemical properties that are driven primarily by long-term abiotic and biotic processes and should be considered drivers of ecosystem functioning, rather than direct measures of functions (Fig. 5).

We propose that much of this discrepancy is due to ambiguity in the definition of an ecosystem function. Although this topic has been discussed in detail (Jax, 2005; Farnsworth et al., 2017) it is clear that uncertainty remains. Much of this debate centers around whether or not ecosystem functions should include only process rates (i.e. enzyme activities, soil respiration rates, etc.), or if additional variables such as nutrient pools (i.e. soil C content, microbial biomass, etc.) or ecosystem properties (i.e. soil texture) (see Fig. 5 for definitions) can also be considered indicators of these functions. We agree with Jax (2005) and Manning *et al*. (2018) that a clear distinction must be made regarding what an appropriate indicator may be to overcome some of the confusion regarding ecosystem functioning. Recently, Manning *et al*. (2018) propose that process rates should be favoured over stocks of energy or matter when measuring ecosystem functions and EMF. However, they also admit that in certain cases, nutrient pools such as soil C stocks or biomass could be considered indicators of longer-term net process rates. Yet in our review we found that only three out of the 82 EMF papers reviewed consisted of functions based solely on process rates (Bradford *et al*. 2014; Eldridge *et al*. 2016; Luo *et al*. 2017). Most papers, instead, included a variety of properties, nutrient pools, and processes (Fig. 5; Table S1).

Similar to the conclusion of Farnsworth et al. (2017), we propose that ecosystem functions are comprised solely on processes, yet these can range from fast processes happening on an hourly or daily timescale (i.e. basal respiration, N_2O production, enzymatic activities, etc.) to slow processes taking months or even decades to assess (i.e. biomass production, changes in soil C accumulation, or habitat provision). Moreover, we propose that ecosystem functions should be assessed by measuring process rates directly, or if the process rates of interest are too slow to measure directly, then the measurement of certain nutrient pools can act as surrogates of these slower processes (Fig. 5). While there is no ideal definition, we feel that this viewpoint is inclusive enough to capture all possible measures of functionality, while also spanning multiple timescales and research foci.

Guidelines for choosing appropriate indicators of ecosystem functions

The selection of appropriate indicators for ecosystem functions is described conceptually in Figure 5. For the processes that can be measured directly (i.e. rates of decomposition, mineralization, enzyme activities, biomass production, etc.), these can be incorporated into EMF metrics, either linked to ecosystem services or not, without any issue (see additional examples given in green in Fig. 5). However, since in most cases it is not realistic to measure processes that require years or decades to assess, such as the build-up of soil fertility over time, it is logical to use specific nutrient pools as indicators to estimate such processes. For example, soil organic carbon and microbial biomass are often used as indicators of soil carbon sequestration and microbial activity, respectively (Table 2). Furthermore, in environments such as drylands, dynamic processes such as soil N transformation rates are strongly related to soil total N (Delgado-Baquerizo *et al.* 2013). For example, one commonly measured indicator for EMF studies is soil mineral N, which is an indicator of the bio-availability of nitrogen in a given system. However, soil mineral N is a) not a process rate, and b) is a very dynamic measure, and thus care must be taken when comparing its value across different times of year or even regions. Thus, while we agree with this approach and find that many nutrient pools are appropriate indicators of a variety of ecosystem functions, we also urge the inclusion of multiple measures over time whenever possible to get better grasp of how temporal changes affect EMF (Bradford *et al.* 2014). These changes could then be described as process rates directly, and would in our opinion better fit the definition of an ecosystem function. Alternatively, after measuring multiple measures over time, an EMF index could be constructed for individual time points and compared to assess temporal changes. Furthermore, in managed ecosystems such as agricultural fields, where N fertilizers are applied annually, such measures cannot be used as indicators of functions related to N cycling. Instead, this variable should be interpreted as another driver of these functions, since the actual value depends on both the timing and quantity of fertilization application.

In contrast to the above examples using processes and nutrient pools as indicators of ecosystem functions, we discourage the use of purely physicochemical properties as indicators of functions (see examples in red in Fig. 5). For example, we found several papers that included soil pH as an indicator for ecosystem functioning (Table S1). From our point of view, however, soil pH is not representative of a 'process that occurs within an ecosystem and may contribute to ecosystem services', but instead is a measure of a general chemical characteristic resulting from weathering of parent materials over long time periods. So, although pH at small scales (i.e. µm up to mm scales such as in the rhizosphere) can be influenced by root exudates and enzymes from plant and soil microbial communities (Hinsinger *et al*. 2003), at the plot- or ecosystem-scale on which most EMF studies focus, we consider soil pH not appropriate to include in an EMF calculation. We acknowledge that this variable is an important driver of soil microbial communities across a wide variety of terrestrial ecosystems (Fierer & Jackson 2006; Maestre *et al*. 2015; Delgado-Baquerizo *et al*. 2018), which in turn affects multiple functions related to nutrient cycling and plant productivity (e.g. Delgado-Baquerizo *et al*. 2016, Trivedi *et al*. 2016; Maron *et al*. 2018), but it cannot be considered as a function itself.

Similarly, other ecosystem properties that are less affected by biological processes and more inherent to a site (i.e. soil texture, slope) or a snapshot of a dynamic process (i.e. soil moisture) should not be included in an EMF index aiming to assess biological drivers on ecosystem functioning. In the case of soil moisture, we recommend instead measuring soil water holding capacity, as this is more indicative of the functional capacity of a soil to hold water, whereas soil moisture content largely depends on recent precipitation events and the time of the year the measurement is taken.

Finally, and regardless of which indicators are measured, we emphasize that it is important for researchers to explain why a particular indicator was used to assess a function, as well as what the impact of that measure is on ecosystem functioning overall. For example, we found that many EMF studies included at least one measure of soil N to represent N cycling, which we agree is very important to ecosystem functioning across all ecosystem types. However, since N cycling is such a broad term, there are many different indicators that fit this general description yet have very different impacts on overall ecosystem functioning (i.e. mineralization, denitrification, total soil N, nitrate, etc.). Without the specific rationale for why a certain measure was made is explicitly stated, the overall meaning and thus the interpretation of the resultant EMF index will be limited. Similarly, although it is clearly important to study and compare the overall values of EMF, we also recommend that researchers present the impact of these different factors on certain key functions individually as well (i.e. crop yield, C-sequestration, etc.) (Giling *et al*. 2018). Not only will this help with choosing meaningful indicators, but we think it will also aid in the understanding of how different functions are related to each other in terms of correlations or trade-offs (Meyer *et al*. 2018), and thus what are the main functions driving the overall trends in EMF.

Future Directions

Despite the usefulness of the EMF concept, it is clear that EMF is extremely broad and that authors conceptualize and thus measure EMF in many different ways. This resembles other popular ecological concepts such as ‘keystone taxa’ (Paine, 1969; Power et al., 1996; Cottee-Jones & Whittaker 2012; Banerjee et al., 2018) and ‘sustainability’ (Kuhlman & Farrington 2010) that are clear conceptually, but differ in both approach and application from study to study. To advance EMF research in the future, we believe that researchers must pay more attention to how they choose, measure, and interpret ecosystem functions (Table 3; Fig. 5). In contrast to creating a set of strict standardized variables for future EMF studies, as has been suggested previously (Meyer *et al*. 2015; Trogish *et al*. 2017), our recommendation is to create a general framework that includes a clear set of EMF definitions and appropriate indicators for ecosystem functions. However, this is by no means the only requirement to move this important concept forward. For example, while many EMF studies have made the link with ecosystem services based on the Millennium Ecosystem Assessment terminology and concepts (MEA 2005), there are many other ecosystem service assessment platforms that could be considered as well (see Carpenter *et al*. 2009; Maes *et al*. 2018). For example, there has recently been a call to incorporate more emphasis on the social and cultural aspects of ecosystems (Díaz *et al*. 2015, 2018). Based on this new outlook and understanding of the importance of assessing the cultural value of ecosystems, what we are referring to as 'ecosystem services' is now moving toward the terminology 'nature's contributions to people', which emphasizes the importance of a more balanced assessment of ecosystem functions and services by incorporating more measures of cultural services that are important for human societies (Díaz *et al*. 2018). However, even this suggestion has triggered much debate from the scientific community (Peterson *et al*. 2018). Furthermore, as we have shown in our review, the majority of EMF studies measure functions within the 'supporting' ecosystem service category, with 392 of the 775 published functions falling in this category (Table S1), and thus there remains no formal consensus on the appropriate terminology to use.

Similarly, while many researchers examine the influence of biodiversity as a driver of EMF (Hector & Bagchi 2007; Zavaleta *et al*. 2010; Lefcheck *et al*. 2014; Luo *et al*. 2017; Meyer *et al*. 2018), some authors consider high biodiversity as an ecosystem service itself (Smukler 2010; van der Plas *et al*. 2016a,b). This begs the question: can biodiversity be considered an ecosystem function or service, or only as a factor explaining EMF? While there are several different opinions on this topic (Maes *et al*. 2018; FAO 2019), which goes beyond the scope of our current objectives, we recommend further discussion on this point until a general agreement can be reached.

Regarding the distinction between EMF studies assessing ecosystem functions only, without a human valuation perspective, versus those in the framework of ecosystem service provision, a practical approach to resolve this issue was proposed by Manning *et al*. (2018). They suggest redefining multifunctionality overall, making a distinction between ecosystem *function* multifunctionality (EF-multifunctionality) and ecosystem *service* multifunctionality (ES-multifunctionality) (see Fig. 1). In line with this, we suggest that studies which measure a more narrowly focused niche of ecosystem functions (i.e. only soil enzyme activities or soil nutrient content), could reflect this emphasis in the title or terminology used (i.e. by studying the impact of drivers on 'soil functioning', 'soil nutrient cycling', or 'soil quality') (Schulte *et al*. 2015; Bünemann *et al*. 2018; Rabot *et al*. 2018). Such a change in terminology would not only make the research goals more obvious to readers, it would also help to reduce ambiguity with the term EMF. Fortunately, we have found that this change is already starting to occur, with terms such as 'soil multifunctionality' (Durán *et al*. 2018; Valencia *et al*. 2018), and is something we encourage others in the EMF to adopt.

Moreover, for studies aiming to assess ecosystem *service* multifunctionality (see Manning et al., 2018) we would like to stress the importance of measuring not only a large quantity of functions (i.e. Meyer *et al*. 2018), but also a broad and diverse set of functions and services that spans across multiple ecosystem service categories in order to give a representative measure of the overall ecosystem functioning. This will also allow a better comprehension of trade-offs between different services in a given system, which can not only help researchers, but land managers and policymakers as well. It is likely that in many cases such a task will require collaboration between researchers in multiple disciplines (i.e. ecologists and sociologists), or at least a transdisciplinary approach (Pohl 2011; Hoffman *et al*. 2017). Yet despite the extra effort that this may require for some researchers, the potential benefits that could be gained by producing a more holistic assessment of EMF would without doubt overcome the efforts involved in producing it.

Concluding remarks

Our goal with this review was to make a critical appraisal of the various functions included in EMF studies, thus shedding light on what is causing ambiguity of this term in order to avoid the degradation of its value and meaning. By summarizing the state of the field, we have shown that the number of ecosystem functions measured is highly variable, ranging from two to 82 per study. Moreover, in most EMF studies there was no clear link between the variables measured and the ecosystem services they contribute to, nor was there any consensus regarding what type of functional indicators are an appropriate measure of a given function. Therefore here we propose: 1) that process rates (ideally, in contrast to nutrient pools and ecosystem properties) should be considered as ecosystems functions; and 2) a set of standardized definitions for ecosystem functions and services, which is supported by examples and explanations for what appropriate indicators may be for such measures. To further improve the utility of EMF studies in the future, we emphasize the need for researchers to explain or justify why certain functions are measured in each study, and how they influence or contribute to ecosystem functioning.

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Tables and Figures

Table 1. Advantages and disadvantages of the use of EMF as a tool to assess and describe the ability of ecosystems to simultaneously provide multiple functions and services. References are given for each example.

	Main Point	References
Advantages	EMF provides a simple metric to assess the overall functioning of ecosystems, or treatments within a single ecosystem, by summarizing multiple variables into one value.	Manning *et al.* 2018
	EMF makes it possible to visualize trade-offs between different ecosystem functions when evaluating overall ecosystem performance.	Allan *et al.* 2015
Disadvantages	The number and type of ecosystem functions used to assess EMF varies greatly among studies, and thus EMF as a metric is not comparable across studies.	This review Hölting *et al.* 2019
	It is difficult to rank and weigh the importance of different ecosystem functions and services when assessing EMF, as this depends on the stakeholders involved (i.e. productivity versus environmental performance for agro-ecosystems is weighed differently by farmers who wish to produce food compared to environmental biologists who wish to protect biodiversity).	Allan *et al.* 2015; Manning *et al.* 2015
	There are many methods available to calculate EMF (each method has its own strengths and weaknesses), which can significantly change outcome of results. Additionally, differences in calculation method can further limit the ability of researchers to compare EMF values.	Bradford et al. 2014; Byrnes et al. 2014; Lefcheck et al. 2015
	In some cases, variables used to calculate EMF do not necessarily reflect ecosystem functions or services, but are instead considered ecosystem properties (e.g. pH, slope of soil).	This review
	EMF is often measured at one single time point, and some functions used to calculate EMF are highly dynamic (e.g. soil mineral N, enzyme activities, etc.).	This review

Table 2: Ecosystem service and functional categories used to organize published functions into groups according to ecosystem service provision they can be linked with. Examples of functions and indicators are given for each category.

Ecosystem service category	Ecosystem services/ Functional category	Functions/services	Indicators
Cultural Nonmaterial benefits obtained from ecosystems	1. Aesthetic values	Cover of flowers	Percentage of flower cover at given time
	2. Recreation and ecotourism	Space for recreation	Inventory of area devoted to hunting grounds; hiking
	3. Spiritual and religious values	Compatibility with local sociocultural values	Survey of community members' attitude toward ecosystem's role in spiritual practices
	4. Mental and physical health	Improving human health	Inventory of improved human health in a particular environment
	5. Habitat provision and biodiversity	Protected areas for habitat restoration	Inventory of environmental conservation areas
		Biodiversity and richness of plant, animal, and microbial species	Species diversity or richness of beetles
Provisioning Products obtained from ecosystems	6. Food production	Food production	Crop yield
			Milk production
		Wild food provision	Wild berry production; wild mushroom production
	7. Raw materials	Timber production	Inventory of tree harvest in given area
		Bioenergy source	Yield of bioenergy substrate production
	8. Quality	Nutrient provision	Grain N concentration
		Palatability	Consumer surveys
		Food safety	Mycotoxin assessment rating
	9. Medicinal resources	Provision of medicinal products	Inventory of products used in medical manufacturing
	10. Fresh water	Providing a source of fresh water	Inventory of fresh water sources and quantities in a given area

	11. Employment	Providing a source of employment	Inventory of jobs created over a given time
	12. Income generation	Providing a source of income	Survey of net income
Regulating Benefits obtained from regulation of ecosystem processes	13. Air quality regulation	Reduction of air pollution	Concentration of NO_x, SO_2, and particulate matter
	14. Climate regulation	C sequestration	Change in soil organic C over time
		Shade provision	Percent cover of shade tree/plant species in given area
		Reduction of greenhouse gas emissions	N_2O, CH_4, CO_2 production
	15. Water regulation	Water conservation	Water infiltration rate
			Soil water holding capacity
	16. Erosion regulation	Soil structure	Comparison of soil aggregate stability
		Planting density	Total plant cover
	17. Water purification	Reducing nitrate leaching	Comparison of soil water nitrate concentration
	18. Disease and pest regulation	Reducing plant diseases or pest predation	Number and abundance of pest species
	19. Pollination	Plant pollination	Abundance of pollinator species
	20. Moderation of extreme events	Reduction of flooding events	Survey of flooded areas over given time period
		minimizing fire risk	Survey of area damaged by fire over given time period
Supporting Services necessary for the production of all other ecosystem services	21. Primary production	Biomass of understory vegetation	Aboveground biomass
			Root biomass
	22. Soil properties and fertility	Soil nutrient storage capacity	Soil phosphorus availability
			Change in total soil nitrogen over time

	23. Nutrient Cycling	Microbial activity	Microbial respiration rates
		Nitrogen cycling	Rates of nitrogen mineralization
		Enzyme activities	Rates of phosphatase activity
		Mycorrhizal associations	AMF root colonization
	24. Photosynthesis	Photosynthetic capacity	Leaf area index

Table 3: Distribution of studies and range of ecosystem functions measured across ecosystem types.

	Ecosystem Type					
	Agroecosystems	Drylands	Forest	Grassland	Other	Overall
Total # studies	22	13	19	25	3	82
Total # individual functions	173	138	183	264	17	775
Avg # functions per study	7.8	10.6	9.8	10.5	5.6	8.9
Median	7	9	5	8	8	8
Range	2-21	5-15	2-28	2-82	4-8	2-82

Figure 1: Conceptual diagram showing that ecosystem multifunctionality (EMF) can be comprised of a) ecosystem functions and services or b) solely ecosystem functions, and that these functions can be measured either directly, or with the use of indicators (see Fig. 5 for guidelines on determining appropriate ecosystem functions and indicators).

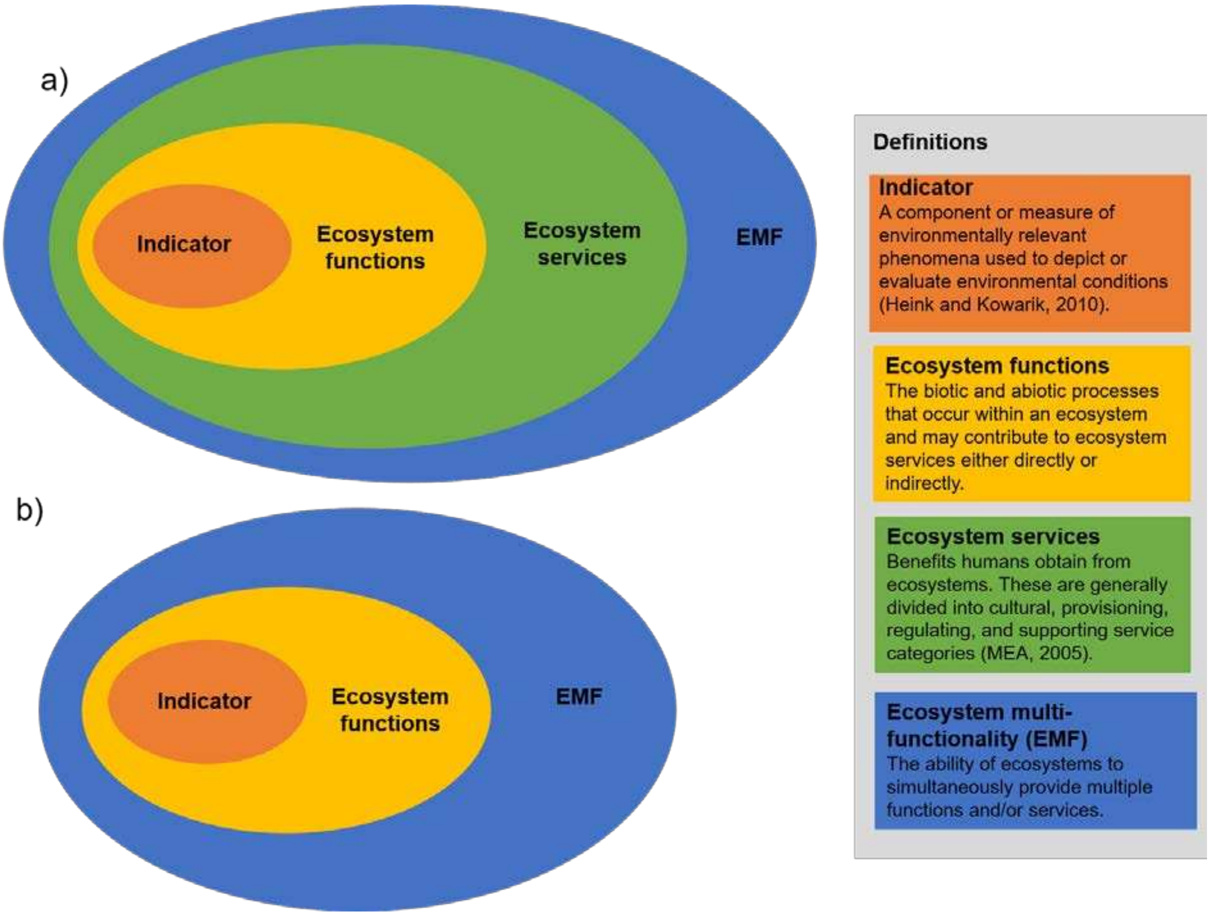


Figure 2: Growth in the number of published EMF studies between 2006 and 2017 as determined by our literature review (details in Table S1).

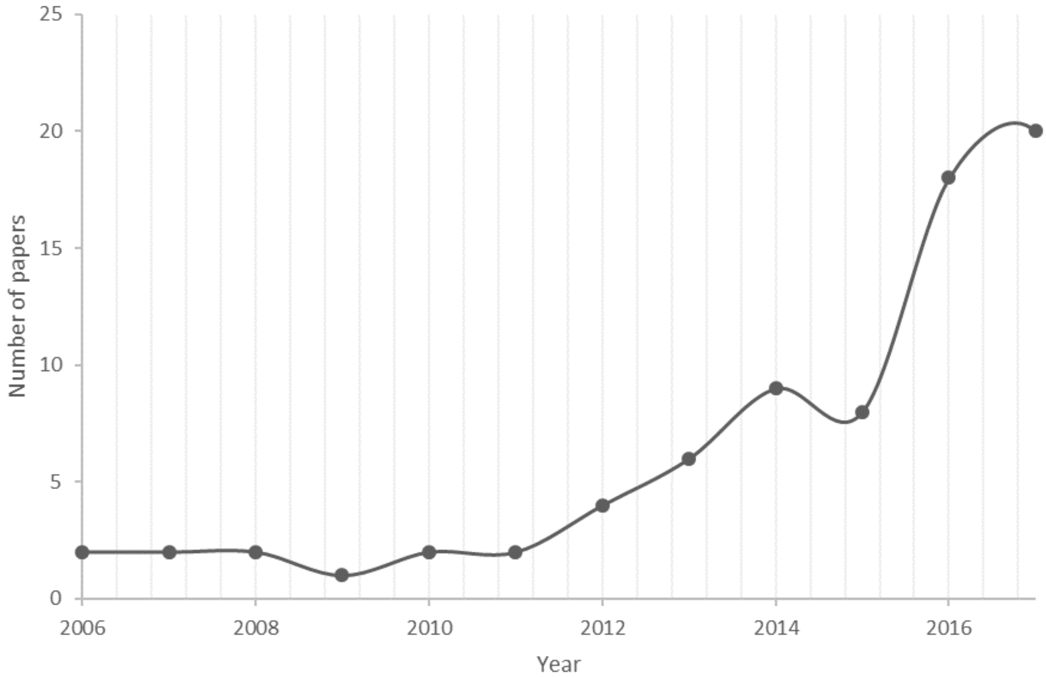


Figure 3: Discrepancy between measurements of EMF in each of the predominant ecosystem types compared to the actual global distribution. The ecosystem types represented in EMF studies are shown in the inner circle (data obtained by our literature review). The global distribution of land-use types is shown in the outer circle (data obtained by the Living Planet Report, WWF 2016). Barren land refers to those ecosystems in which less than one third of the area has vegetation or other cover. In general, barren land has thin soil, sand, or rocks and includes areas such as deserts, dry salt flats, beaches, sand dunes, exposed rock, strip mines, quaries, and gravel pits.

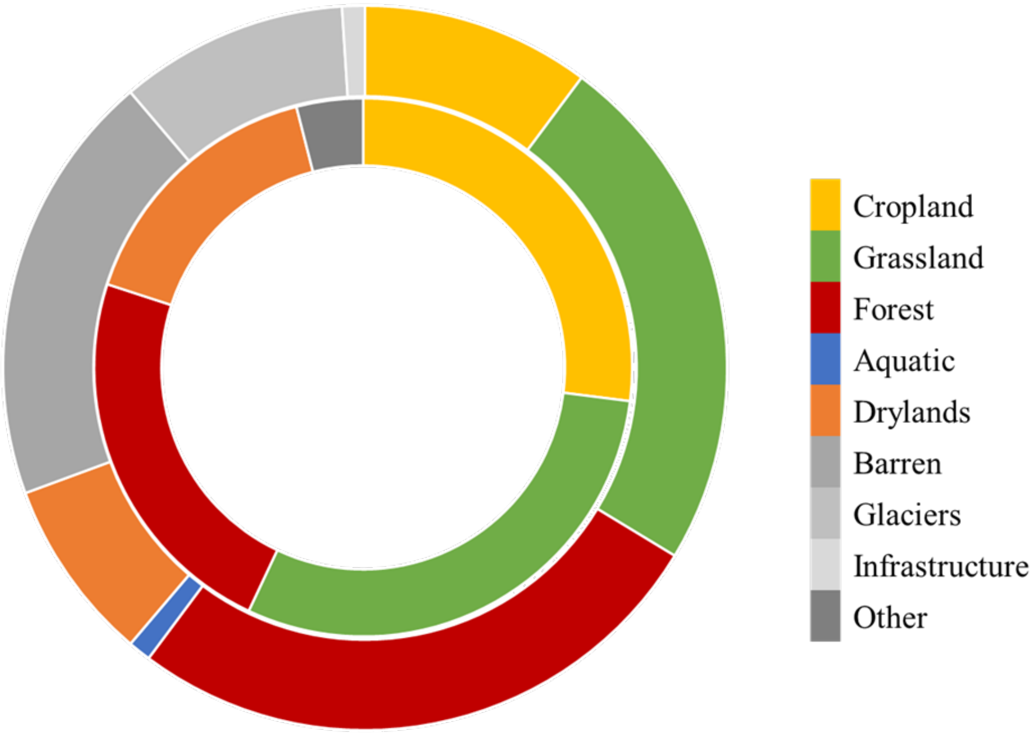


Figure 4: Distribution of the number of measured functions within the different ecosystem service/functional categories across terrestrial ecosystems.

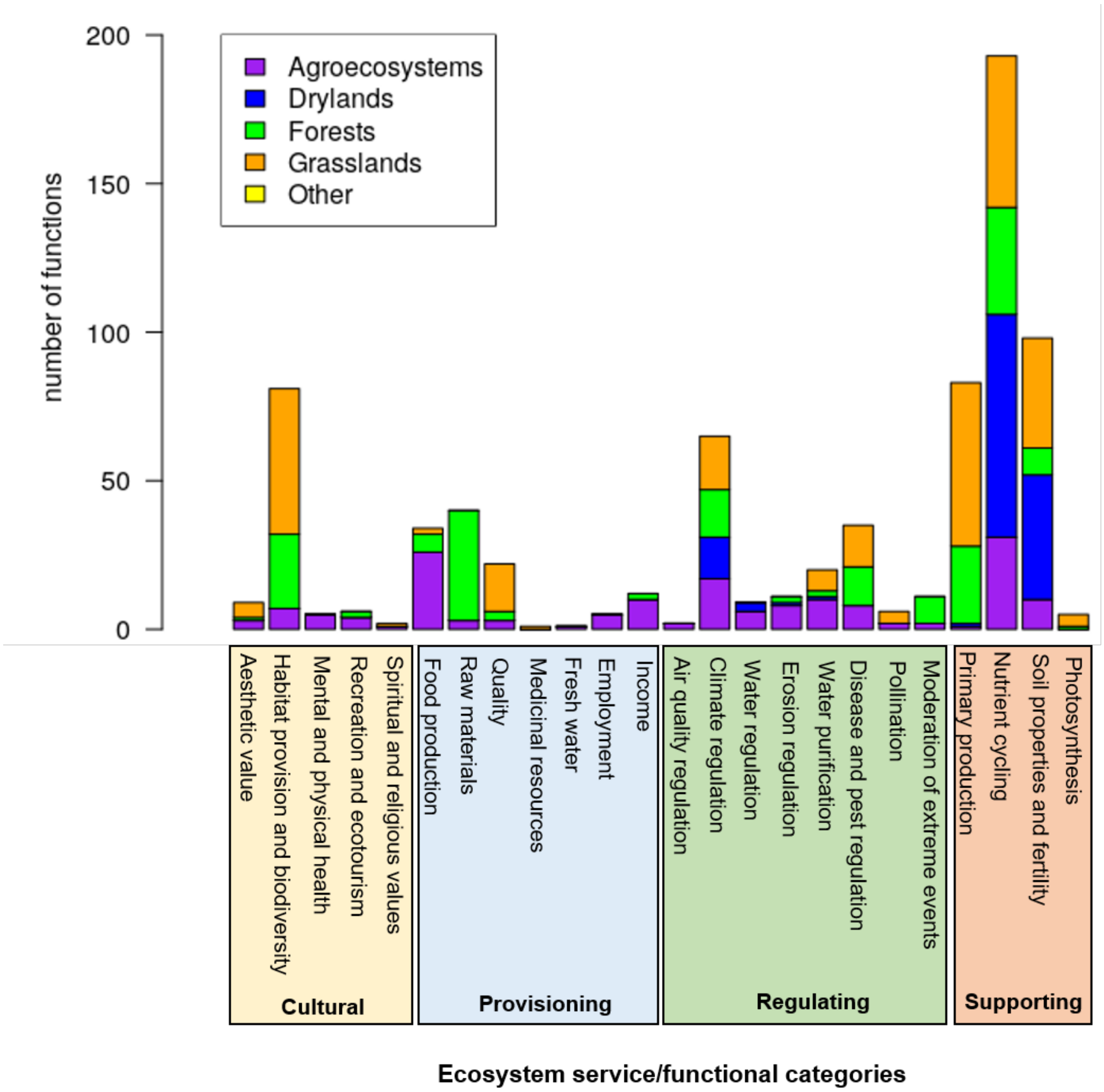
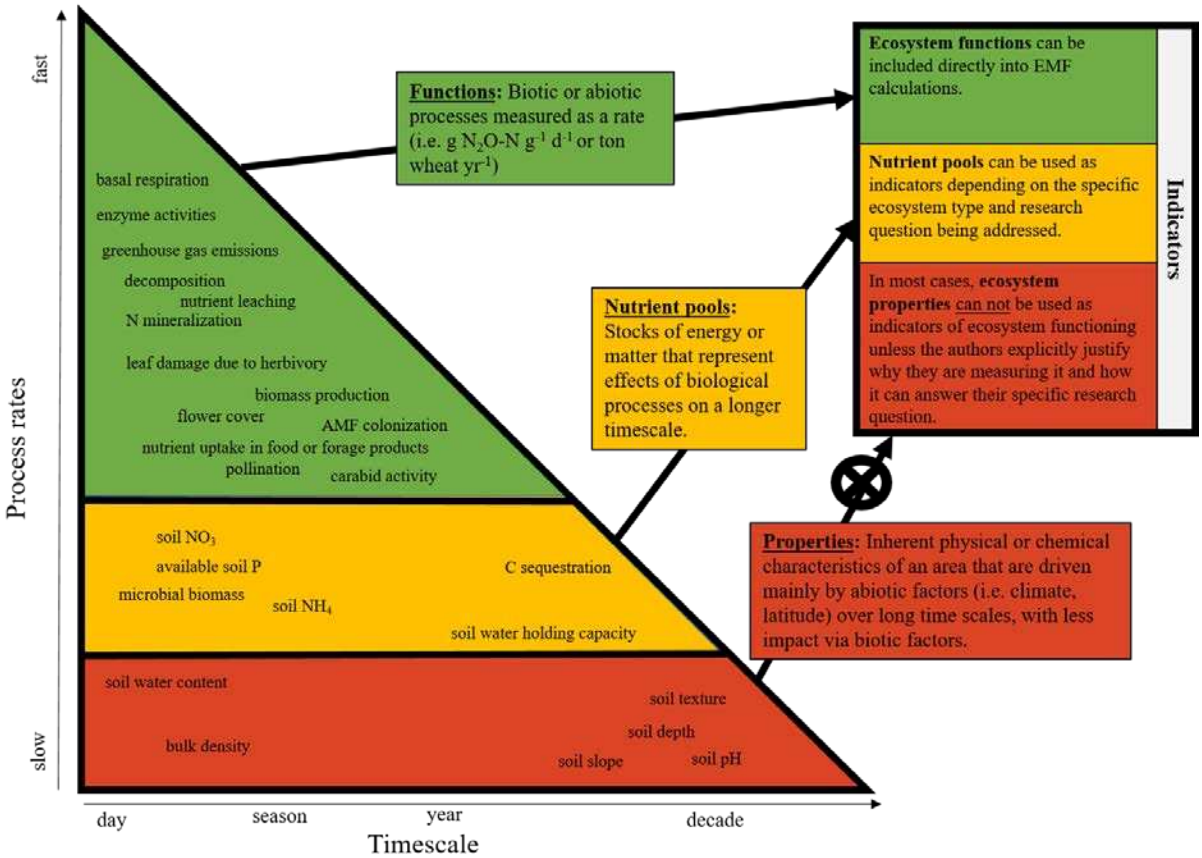


Figure 5: Conceptual diagram representing differences between ecosystem functions, nutrient pools, and properties and how they can be used as indicators for the calculation of EMF indices. All the variables shown here are examples of functions published in the EMF literature reviewed in this study. Direct measures of biotic or abiotic processes are considered ecosystem functions and can be included in the EMF calculation directly (green). On the other hand, processes that take place on slower timescales (i.e. soil C sequestration) or stocks of energy that are representative of slower biotic or abiotic processes (i.e. microbial biomass) can also be used as indicators of certain ecological functions (yellow). However, it is critical that the chosen indicator be appropriate for the specific research question addressed as well as the particular ecosystem type. In contrast, ecosystem properties (shown in red) are considered inherent physical or chemical characteristics of an ecosystem that are mainly driven by abiotic factors over very long timescales. In these cases, we caution against the use of ecosystem properties as indicators of ecosystem functions unless there is clear evidence given in the study that such variables can act as valid indicators of ecosystem functions. Once appropriate functions and/or indicators are determined for a given study, these can then be used to calculate EMF, either with or without the inclusion of ecosystem services (see Fig. 1).



Supplementary material

Table S1: Summary of literature review including ecosystem type, methodology used to calculate EMF, the number of functions per study, as well as the specific functions included in the calculation. Paper type refers to A) papers that calculate EMF (i.e. direct assessment) and B) papers that measure multiple functions and discuss the results in the context of EMF (i.e. indirect assessment). The EMF Index Approach refers to how the EMF value was calculated: 1) averaging of Z-scores, 2) threshold approach, 3) PCA axis scoring, 4) Other (i.e. comparing maps of different ecosystem function rankings), and 5) Analytical Hierarchy Approach. We classified the published functions into functional and ecosystem service categories based on the concepts and examples given in Table 2 and Figure 5. Variables in red were not considered ecosystem functions (i.e. 20 out of the published 775 functions). References are given below.

Reference	Paper type	EMF Index .	Number of .	Functions measured	Functional Category	Ecosystem Service Category
Agus et al., 2006	B	4	8	Soil loss from paddy field	Erosion regulation	Regulating
				Flood mitigation	Moderation of extreme events	Regulating
				Nitrate content in ground water	Water purification	Regulating
				Replacement cost of flood mitigation function		
				Replacement cost of heat mitigation function		
				Replacement cost of preserving rural amenities for recreation function		
				Replacement cost of waste disposal function		
				Replacement cost of water preservation function		
				carbon sequestration	Climate regulation	Regulating
				water buffering	Water regulation	Regulating

Birkhofer et al. 2018	A	1	8	Soil organic carbon	Climate regulation	Regulating
				Biological control	Disease and pest regulation	Regulating
				Yield potential	Food production	Provisioning
				Conservation	Habitat provision and biodiversity	Cultural
				Pollination	Pollination	Regulating
				Hunting	Recreation and ecotourism	Cultural
				Plant-available P	Soil properties and fertility	Supporting
				Total nitrogen	Soil properties and fertility	Supporting
Blesh 2017	A	2	4	Total above-ground biomass porduction	Food production	Provisioning
				Weed suppression	Food production	Provisioning
				Nitrogen retention in biomass	Nutrient cycling	Supporting
				Nitrogen suply from biological N fixation in legume	Nutrient cycling	Supporting
Câmara Ferreira et al., 2016	B	4	4	SOC	Climate regulation	Regulating
				microbial biomass	Nutrient cycling	Supporting
				microbial respiration	Nutrient cycling	Supporting
				total N	Soil properties and fertility	Supporting

Finney and Kaye, 2017	A	1	5	subsequent maize yield	Food production	Provisioning
				weed suppression	Food production	Provisioning
				N retention	Nutrient cycling	Supporting
				aboveground biomass of cover crops	Primary production	Supporting
				inorganic N supply during subsequent growing season	Soil properties and fertility	Supporting
Guo et al., 2015	A	4	5	sustainable production capacity	Food production	Provisioning
				production function (Crop)	Food production	Provisioning
				economic function	Income generation	Provisioning
				security function (living standards of rural residents)	Mental and physical health	Cultural
				supply function (food safety)	Quality	Provisioning
He et al., 2009	B	4	9	organic C	Climate regulation	Regulating
				nitrogen mineralization	Nutrient cycling	Supporting
				potential ammonia oxidation	Nutrient cycling	Supporting
				respiration rate	Nutrient cycling	Supporting
				soil microbial biomass carbon	Nutrient cycling	Supporting
				ammonium	Soil properties and fertility	Supporting

				available K	Soil properties and fertility	Supporting
				available P	Soil properties and fertility	Supporting
				nitrate	Soil properties and fertility	Supporting
Holt et al., 2016	B	4	9	recreation and aesthetics	Aesthetic values/Recreation and ecotourism	Cultural
				disease and pest control	Disease and pest resistance	Regulating
				erosion control (soil sediment)	Erosion regulation	Regulating
				non-crop food production	Food production	Provisioning
				water supply	Fresh water	Provisioning
				pollination	Pollination	Regulating
				fibre production	Raw materials	Provisioning
				water quality	Water purification	Regulating
				pollution attenuation	Water regulation	Regulating
Huang et al., 2006	B	4	7	air purification	Air quality regulation	Regulating
				cooling temperature	Climate regulation	Regulating
				soil erosion prevention	Erosion regulation	Regulating
				flood mitigation	Moderation of extreme events	Regulating

				health and recreation	Recreation and ecotourism/Mental and physical health	Cultural
				water purification	Water purification	Regulating
				fostering water resources	Water regulation	Regulating
Iverson et al., 2014	B	4	2	reduction in pest abundance or plant damage, increase in natural enemy abundance	Disease and pest resistance	Regulating
				grams of consumable product per plant	Food production	Provisioning
Liang et al., 2017	A	4	3	soil ammonification	Nutrient cycling	Supporting
				soil nitrification potential	Nutrient cycling	Supporting
				soil respiration	Nutrient cycling	Supporting
Liebman et al., 2013	B	4	6	erosion	Erosion regulation	Regulating
				yield	Food production	Provisioning
				bird richness	Habitat provision and biodiversity	Cultural
				net returns	Income generation	Provisioning
				N leaching loss	Water purification	Regulating
				P loss	Water purification	Regulating
Luo et al., 2017	A	1	12	Acid phosphomonoesterase	Nutrient Cycling	Supporting

				Alkaline phosphomonoesterase	Nutrient Cycling	Supporting
				Leucine amino peptidase	Nutrient cycling	Supporting
				Peroxidase	Nutrient cycling	Supporting
				Phenol oxidase	Nutrient cycling	Supporting
				Sulfatase	Nutrient cycling	supporting
				Urease	Nutrient cycling	Supporting
				α-1,4-Glucosidase	Nutrient cycling	Supporting
				β-1,4-Glucosidase	Nutrient cycling	Supporting
				β-1,4-N-Acetyl-glucosaminidase	Nutrient cycling	Supporting
				β-1,4-Xylosidase	Nutrient cycling	Supporting
				β-D-Cellobiohydrolase	Nutrient cycling	Supporting
Mitchell et al., 2014	B	4	8	soil organic matter	Climate regulation	Regulating
				aphid regulation	Disease and pest regulation	Regulating
				herbivory regulation	Disease and Pest regulation	Regulating
				crop yield	Food production	Provisioning
				cotton decomposition	Nutrient cycling	Supporting

				litter decomposition	Nutrient cycling	Supporting
				soil P saturation (%P binding sites occupied)	Nutrient cycling	Supporting
				soil N	Soil properties and fertility	Supporting
Parra-López et al., 2008	A	5	21	presence of agriculture in problematic or disadvantaged regions	Aesthetic values	Cultural
				less atmospheric pollution	Air quality regulation	Regulating
				autonomy from institutional subsidies	Employment	Provisioning
				direct local employment	Employment	Provisioning
				indirect local employment	Employment	Provisioning
				trade and sale opportunities	Employment	Provisioning
				less soil erosion	Erosion regulation	Regulating
				harvest growing success prospects	Food production	Provisioning
				productivity	Food production	Provisioning
				biodiversity	Habitat provision and biodiversity	Cultural
				income	Income generation	Provisioning
				independence from external to agriculture inputs	Income generation	Provisioning
				stability of income over time	Income generation	Provisioning

			farmers work health conditions	Mental and physical health	Cultural
			social justice in rural areas	Mental and physical health	Cultural
			olive oil quality	Quality	Provisioning
			recreational use	Recreation and ecotourism	Cultural
			soil fertility	Soil properties and fertility	Supporting
			compatibility with local sociocultural values	Spiritual and religious values	Cultural
			less water contamination	Water purification	Regulating
			rational use of irrigation water	Water regulation	Regulating
Peng et al., 2015	A	1, 4, 5	10	Proportion of primary industry labor	Employment	Provisioning
			Grain output per acre cultivated land	Food production	Provisioning
			Mean normalized difference vegetation index (NDVI) of cultivated land	Food production	Provisioning
			Gross output value of agricultural products per acre cultivated land	Income generation	Provisioning
			Income ratio of agricultural sightseeing garden	Income generation	Provisioning
			Rural population supported per acre cultivated land	Income generation	Provisioning
			Visitors' ratio of agricultural sightseeing garden	Recreation and ecotourism	Cultural
			average fertiliser usage in cultivated land		

				average pesticide usage in cultivated land Rural biogas popularity rate		
Schipanski et al., 2014	A	4	13	N2O reduction	Climate regulation	Regulating
				Soil C storage	Climate regulation	Regulating
				Pest suppression	Disease and pest regulation	Regulating
				Erosion control	Erosion regulation	Regulating
				biomass production	Food production	Provisioning
				Food production	Food production	Provisioning
				Weed suppression	Food production	Provisioning
				Beneficial insect conservation	Habitat provision and biodiversity	Cultural
				Profitability	Income generation	Provisioning
				Management ease (risk)	Mental and physical health	Cultural
				AMF colonization	Nutrient cycling	Supporting
				N mineralization	Nutrient cycling	Supporting
				NO3 retention	Nutrient cycling	Supporting
Smukler et al., 2010	B	4	14	C content of litter	Climate regulation	Regulating
				C content of roots	Climate regulation	Regulating

			C content of shrubs	Climate regulation	Regula ting
			C content of sub soil (15-30cm)	Climate regulation	Regula ting
			C content of top soil (0-15cm)	Climate regulation	Regula ting
			C content of trees	Climate regulation	Regula ting
			mean GHG emissions	Climate regulation	Regula ting
			sediment loss	Erosion regulation	Regula ting
			yield	Food production	Provisi oning
			earthworm diversity	Habitat provision and biodiversity	Cultur al
			microbial diversity	Habitat provision and biodiversity	Cultur al
			nematode diversity	Habitat provision and biodiversity	Cultur al
			nitrate leaching	Water purification	Regula ting
			infiltration rate	Water regulation	Regula ting
Tao et al., 2014	A	4	5	sustainable production capacity	Food production	Provisi oning
			production function (Crop)	Food production	Provisi oning
			economic function	Income generation	Provisi oning
			security function (living standards of rural residents)	Mental and physical health	Cultur al

				supply function (food safety)	Quality	Provisioning
Tipraqsa et al., 2007	B	4	7	Richness of food species (number)	Food production	Provisioning
				Share of home produced food (%)	Food production	Provisioning
				Tree growth	Raw materials	Provisioning
				Soil organic matter (%)	Climate regulation	Regulating
				Share of months in dry season irrigated (%)	Water regulation	Regulating
				Agricultural productivity	Food production	Provisioning
				Richness of species for social purposes (number)	Aesthetic values	Provisioning
Valujeva et al., 2016	A	4	3	increased milk production	Food production	Provisioning
				annual planting rate of new afforestation	Raw materials	Provisioning
				NO3 conc. in groundwater	Water purification	Regulating
Van Vooren et al., 2017	A	4	8	C stock	Climate regulation	Regulating
				predator density	Disease and pest regulation	Regulating
				predator diversity	Disease and pest regulation	Regulating
				soil sediment interception	Erosion regulation	Regulating
				crop yield	Food production	Provisioning

			P interception	Nutrient cycling	Suppor ting
			N interception at subsurface	Water purification	Regula ting
			N interception at surface	Water purification	Regula ting
Bowker et al., 2013	A	4	6 organic C	Climate regulation	Regula ting
			b-glucosidase activity	Nutrient cycling	Suppor ting
			phosphatase activity	Nutrient cycling	Suppor ting
			respiration	Nutrient cycling	Suppor ting
			urease activity	Nutrient cycling	Suppor ting
			total N	Soil properties and fertility	Suppor ting
Chandregowda et al., 2018	A	1	1 1 Soil organic matter	Climate regulation	Regula ting
			Total soil C	Climate regulation	Regula ting
			Basal respiration	Nutrient cycling	Suppor ting
			Microbial biomass C	Nutrient cycling	Suppor ting
			Microbial biomass N	Nutrient cycling	Suppor ting
			N-mineralization rate	Nutrient cycling	Suppor ting
			ammonium concentration	Soil properties and fertility	Suppor ting

			nitrate concentration	Soil properties and fertility	Suppor ting
			Soil C:N ratio	Soil properties and fertility	Suppor ting
			Total soil N	Soil properties and fertility	Suppor ting
			Metabolic-quotient	Supporting	Suppor ting
Delgado-Baquerizo et al., 2016a	A	1	5	organic C	Climate regulation	Regula ting
			b-glucosidase	Nutrient cycling	Suppor ting
			phosphatase activity	Nutrient cycling	Suppor ting
			Olsen inorganic P	Soil properties and fertility	Suppor ting
			total N	Soil properties and fertility	Suppor ting
Delgado-Baquerizo et al., 2016b	A	1	6	DNA concentration	Nutrient cycling	Suppor ting
			potential net nitrogen mineralization	Nutrient cycling	Regula ting
			plant productivity	Primary production	Suppor ting
			ammonium concentration	Soil properties and fertility	Suppor ting
			available P	Soil properties and fertility	Suppor ting
			nitrate concentration	Soil properties and fertility	Suppor ting
Delgado-Baquerizo et al., 2017	A	4	8	carbohydrate availability	Nutrient cycling	Suppor ting

				cellulose degradation	Nutrient cycling	Suppor ting
				chitin degradation	Nutrient cycling	Regula ting
				organic P mineralization	Nutrient cycling	Suppor ting
				starch degradation	Nutrient cycling	Suppor ting
				ammonium availability	Soil properties and fertility	Suppor ting
				nitrate availability	Soil properties and fertility	Suppor ting
				phosphorus availability	Soil properties and fertility	Suppor ting
Duran et al., 2018	A	1	14	Soil organic carbon	Climate regulation	Regula ting
				b-glucosidase activity	Nutrient cycling	Suppor ting
				Phosphatase activity	Nutrient cycling	Suppor ting
				Potential net N mineralization	Nutrient cycling	Suppor ting
				Soil amino acids	Nutrient cycling	Suppor ting
				Soil aromatic compounds	Nutrient cycling	Suppor ting
				Soil pentose	Nutrient cycling	Suppor ting
				Soil phenols	Nutrient cycling	Suppor ting
				Soil proteins	Nutrient cycling	Suppor ting

				Available P	Soil properties and fertility	Supporting
				Soil ammonium	Soil properties and fertility	Supporting
				Soil hexoses	Soil properties and fertility	Supporting
				Soil nitrate	Soil properties and fertility	Supporting
				Total N	Soil properties and fertility	Supporting
Garibotti et al., 2018	A	1, 2	9	Soil organic carbon	Climate regulation	Regulating
				Soil stability test (cohesion of soil fragments)	Erosion regulation	Regulating
				Potential net N mineralization	Nutrient cycling	Supporting
				Ammonium	Soil properties and fertility	Supporting
				Available P (Olson)	Soil properties and fertility	Supporting
				Nitrate	Soil properties and fertility	Supporting
				Total N	Soil properties and fertility	Supporting
				water infiltration	Water regulation	Regulating
				soil moisture		
Jucker and Coomes, 2012	A	1	14	organic C	Climate regulation	Regulating
				amino acids	Nutrient cycling	Supporting

				aromatic compound	Nutrient cycling	Suppor ting
				hexoses	Nutrient cycling	Suppor ting
				pentoses	Nutrient cycling	Suppor ting
				phenols	Nutrient cycling	Suppor ting
				phosphatase activity	Nutrient cycling	Suppor ting
				potential N transformation rates	Nutrient cycling	Suppor ting
				proteins	Nutrient cycling	Suppor ting
				ß-glucosidase	Nutrient cycling	Suppor ting
				ammonium	Soil properties and fertility	Suppor ting
				available inorganic P	Soil properties and fertility	Suppor ting
				nitrate	Soil properties and fertility	Suppor ting
				total N	Soil properties and fertility	Suppor ting
Liu et al., 2017	A	1	15	CH4 flux	Climate regulation	Regula ting
				CO2 flux	Climate regulation	Regula ting
				N2O flux	Climate regulation	Regula ting
				a-glucosidase	Nutrient Cycling	Suppor ting

				b-D-cellulosidase	Nutrient cycling	Supporting
				b-D-glucopyranoside	Nutrient cycling	Supporting
				b-xylosidase	Nutrient cycling	Supporting
				L-Leucine-7-amido-4-methylcoumarin hydrochloride	Nutrient cycling	Supporting
				microbial biomass	Nutrient cycling	Supporting
				microbial biomass	Nutrient cycling	Supporting
				N-acetyl-b-glucosaminidase	Nutrient cycling	Supporting
				phosphate	Nutrient cycling	Supporting
				potential nitrification rate	Nutrient cycling	Supporting
				available N	Soil properties and fertility	Supporting
				dissolved organic carbon	Soil properties and fertility	Supporting
Maestre et al., 2012a	A	1	14	organic C	Climate regulation	Regulating
				amino acids	Nutrient cycling	Supporting
				aromatic compound	Nutrient cycling	Supporting
				hexoses	Nutrient cycling	Supporting
				pentoses	Nutrient cycling	Supporting

				phenols	Nutrient cycling	Supporting
				phosphatase activity	Nutrient cycling	Supporting
				potential N transformation rates	Nutrient cycling	Supporting
				proteins	Nutrient cycling	Supporting
				ß-glucosidase	Nutrient cycling	Supporting
				ammonium	Soil properties and fertility	Supporting
				available inorganic P	Soil properties and fertility	Supporting
				nitrate	Soil properties and fertility	Supporting
				total N	Soil properties and fertility	Supporting
Maestre et al., 2012b	A	1	14	organic C	Climate regulation	Regulating
				amino acids	Nutrient cycling	Supporting
				aromatic compound	Nutrient cycling	Supporting
				hexoses	Nutrient cycling	Supporting
				pentoses	Nutrient cycling	Supporting
				phenols	Nutrient cycling	Supporting
				phosphatase activity	Nutrient cycling	Supporting

				potential N transformation rates	Nutrient cycling	Supporting
				proteins	Nutrient cycling	Supporting
				ß-glucosidase	Nutrient cycling	Supporting
				ammonium	Soil properties and fertility	Supporting
				available inorganic P	Soil properties and fertility	Supporting
				nitrate	Soil properties and fertility	Supporting
				total N	Soil properties and fertility	Supporting
Valencia et al., 2015	A	1	13	organic C	Climate regulation	Regulating
				amino acids	Nutrient cycling	Supporting
				b-glucosidase activity	Nutrient cycling	Supporting
				hexoses	Nutrient cycling	Supporting
				net potential mineralization rate	Nutrient cycling	Supporting
				pentoses	Nutrient cycling	Supporting
				phosphatase activity	Nutrient cycling	Supporting
				proteins	Nutrient cycling	Supporting
				available inorganic P	Soil properties and fertility	Supporting

				Olsen P	Soil properties and fertility	Supporting
				total available N	Soil properties and fertility	Supporting
				total nitrogen (N)	Soil properties and fertility	Supporting
				total phosphorus (P)	Soil properties and fertility	Supporting
Zhang et al., 2016	A	1	9	shading by plant canopies	Climate regulation	Regulating
				mineralisable nitrogen	Nutrient cycling	Supporting
				phosphatase	Nutrient cycling	Supporting
				soil respiration	Nutrient cycling	Supporting
				ß-glucosidase	Nutrient cycling	Supporting
				dissolved nitrogen	Soil properties and fertility	Supporting
				sorptivity	Water purification	Regulating
				infiltration index	Water regulation	Regulating
				steady-state infiltration	Water regulation	Regulating
Mori et al., 2016	A	1, 2	5	soil C sequestration	Climate regulation	Regulating
				litter decomposition	Nutrient cycling	Supporting
				belowground primary production	Primary production	Supporting

				plant-available N	Soil properties and fertility	Suppor ting
				N leaching losses	Water purification	Regula ting
Ratcliffe et al., 2017	A	1, 2	2 6	drought resistance	Climate regulation	Regula ting
				soil C stock	Climate regulation	Regula ting
				resistance to insect damage	Disease and pest regulation	Regula ting
				resistance to mammal browsing	Disease and pest regulation	Regula ting
				resistance to pathogen damage	Disease and pest regulation	Regula ting
				earthworm biomass	Nutrient cycling	Suppor ting
				litter decomposition	Nutrient cycling	Suppor ting
				microbial biomass	Nutrient cycling	Suppor ting
				N resorption efficiency	Nutrient cycling	Suppor ting
				wood decomposition	Nutrient cycling	Suppor ting
				photosynthetic efficiency	Photosynthesis	Suppor ting
				fine root biomass	Primary production	Suppor ting
				fine woody debris	Primary production	Suppor ting
				leaf mass	Primary production	Suppor ting

			litter production	Primary production	Suppor ting
			understory biomass	Primary production	Suppor ting
			sapling growth	Raw materials	Provisi oning
			tree biomass	Raw materials	Provisi oning
			tree growth recovery	Raw materials	Provisi oning
			tree growth resilience	Raw materials	Provisi oning
			tree growth resistance	Raw materials	Provisi oning
			tree growth stability	Raw materials	Provisi oning
			tree juvenile regeneration	Raw materials	Provisi oning
			tree productivity	Raw materials	Provisi oning
			tree seedling regeneration	Raw materials	Provisi oning
			soil C/N ratio	Soil properties and fertility	Suppor ting
Constan-Nava et al., 2015	A	1	5	soil organic matter	Climate regulation	Regula ting
			acid phosphatase activity	Nutrient Cycling	Suppor ting
			b-glucosidase activity	Nutrient cycling	Suppor ting
			understory plant dry biomass	Primary production	Suppor ting

				available P	Soil properties and fertility	Supporting
van der Plas et al., 2016a	A	2	16	soil carbon stock	Climate regulation	Regulating
				resistance to insect herbivory	Disease and pest regulation	Regulating
				resistance to mammal browsing	Disease and pest regulation	Regulating
				resistance to pathogen damage	Disease and pest regulation	Regulating
				bat diversity	habitat provision and biodiversity	Cultural
				bird diversity	Habitat provision and biodiversity	Cultural
				understory plant diversity	Habitat provision and biodiversity	Cultural
				resistance to drought	Moderation of extreme events	Regulating
				earthworm biomass	Nutrient cycling	Supporting
				litter decomposition	Nutrient cycling	Supporting
				microbial biomass	Nutrient cycling	Supporting
				wood decomposition	Nutrient cycling	Supporting
				root biomass	Primary production	Supporting
				wood quality	Quality	Provisioning
				timber production	Raw materials	Provisioning

			tree regeneration	Raw materials	Provisioning
van der Plas et al., 2016b	A	2	16	soil carbon stock	Climate regulation	Regulating
			resistance to browsing	Disease and pest regulation	Regulating
			resistance to insects	Disease and pest regulation	Regulating
			resistance to pathogens	Disease and pest regulation	Regulating
			bat diversity	habitat provision and biodiversity	Cultural
			bird diversity	Habitat provision and biodiversity	Cultural
			understory diversity	Habitat provision and biodiversity	Cultural
			resistance to drought	Moderation of extreme events	Regulating
			earthworm biomass	Nutrient cycling	Supporting
			litter decomposition	Nutrient cycling	Supporting
			microbial biomass	Nutrient cycling	Supporting
			wood decomposition	Nutrient cycling	Supporting
			root biomass	Primary production	Supporting
			timber quality	Quality	Provisioning
			timber production	Raw materials	Provisioning

				tree regeneration	Raw materials	Provisioning
Eldridge et al., 2016	A	1	4	cellobiosidase activity	Nutrient cycling	Supporting
				cellulose degradation	Nutrient cycling	Supporting
				N-acetyl-B-glucosaminidase	Nutrient cycling	Supporting
				phosphatase	Nutrient cycling	Supporting
Bastida et al., 2017	A	1	6	b-glucosidase	Nutrient cycling	Supporting
				cellobiohydrolase	Nutrient cycling	Supporting
				N-acetylglucosaminidase	Nutrient cycling	Supporting
				phosphomonoesterase	Nutrient cycling	Supporting
				Polyphenol oxidase	Nutrient cycling	Supporting
				urease	Nutrient cycling	Supporting
Sacchelli et al., 2013	A	4	5	slope		
				soil bearing capacity		
				soil depth		
				protected area	habitat conservation and biodiversity	Cultural
				fire risk	Moderation of extreme events	Regulating
				productive forest with tourist value	Recreation and ecotourism	Cultural

			soil comapction risk	Soil properties and fertility	Suppor ting
Schulz and Shroder, 2016	A	4	3	potential C sequestration	Climate regulation	Regula ting
			potential erosion prevention	Erosion regulation	Regula ting
			potential habitat function (connectivity)	Habitat provision	Cultur al
Lohbeck et al., 2016	B	4	4	wood decomposition	Nutrient cycling	Suppor ting
			litter production	Primary production	Suppor ting
			primary productivity	Primary production	Suppor ting
			aboveground biomass	Raw materials	Provisi oning
Gamfeldt et al., 2013	B	4	6	soil carbon storage	Climate regulation	Regula ting
			berry production	Food production	Provisi oning
			understory plant species richness	Habitat provision and biodiversity	Cultur al
			occurrence of dead wood	Primary production	Suppor ting
			Tree biomass production	Raw materials	Provisi oning
			game production potential	Recreation and ecotourism	Cultur al
Trivino et al., 2017	B	4	3	C storage	Climate regulation	Regula ting
			biodiversity (i.e. habitat)	Habitat provision and biodiversity	Cultur al

				timber harvest revenues	Income generation	Provisioning
Irauschek et al., 2017	B	4	14	C in trees, standing deadwood, coarse woody debris, and soil C	Climate regulation	Regulating
				volume killed by bark beetles	Disease and pest regulation	Regulating
				landslide and erosion protection	Erosion regulation	Regulating
				bird habitat quality	Habitat provision and biodiversity	Cultural
				avalanche protection index	Moderation of extreme events	Regulating
				basal area share of Abies alba	Primary production	Supporting
				basal area share of broadleaves	Primary production	Supporting
				standing deadwood volume	Primary production	Supporting
				annual net volume increment	Raw materials	Provisioning
				annual volume harvested	Raw materials	Provisioning
				large living trees	Raw materials	Provisioning
				standing volume living trees	Raw materials	Provisioning
				tree size diversity (mean Shannon diversity of DBH and height)	Raw materials	Provisioning
				tree species diversity	Raw materials	Provisioning
Schuler et al., 2017	B	4	3	habitat quality	Habitat provision and biodiversity	Cultural

				protection from gravitational hazards	Moderation of extreme events	Regulating
				aboveground biomass	Raw materials	Provisioning
Hazard et al., 2017	B	4	4	CO2 efflux	Climate regulation	Regulating
				fungal productivity	Nutrient cycling	Supporting
				plant productivity	Primary production	Supporting
				soil nutrient contentration in leachate	Water purification	Regulating
Granath et al., 2018	B	4	2	density of 2 species of berry (berry production)	Food production	Provisioning
				density of 2 species of berry (berry production)	Food production	Provisioning
Peura et al., 2018	A	1	16	Scenic beauty	Aesthetic values	Cultural
				Carbon sequestration	Climate regulation	Regulating
				Carbon storage	Climate regulation	Regulating
				Cowberry	Food production	Provisioning
				Mushroom	Food production	Provisioning
				HSI Capercaillie	Habitat provision and biodiversity	Cultural
				HSI Hazel grouse	Habitat provision and biodiversity	Cultural
				HSI Lesser spotted wood pecker	Habitat provision and biodiversity	Cultural

				HSI Long-tailed tit	Habitat provision and biodiversity	Cultural
				HSI Siberian flying squirrel	Habitat provision and biodiversity	Cultural
				HSI Three-toed woodpecker	Habitat provision and biodiversity	Cultural
				Dead wood	Primary production	Supporting
				Bilberry	provisioning	
				Harvested timber	Raw materials	Provisioning
				Large trees	Raw materials	Provisioning
				Timber NPV	Raw materials	Provisioning
Van der Plas et al., 2018	A	1	28	Soil Carbon Stock	Climate regulation	Regulating
				Resist. to insects	Disease and pest regulation	Regulating
				Resist. to pathogens	Disease and pest regulation	Regulating
				Resistance to browsing	Disease and pest regulation	Regulating
				Bat diversity	habitat provision and biodiversity	Cultural
				Bird diversity	Habitat provision and biodiversity	Cultural
				Spider diversity	Habitat provision and biodiversity	Cultural
				Understorey diversity	Habitat provision and biodiversity	Cultural

Resist. to drought	Moderation of extreme events	Regulating
Earthworm biomass	Nutrient cycling	Supporting
Litter decomp.	Nutrient cycling	Supporting
Microbial biomass	Nutrient cycling	Supporting
Nutrient Resorption efficiency	Nutrient cycling	Supporting
Wood decomp.	Nutrient cycling	Supporting
Coarse woody debr.	Primary production	Supporting
Litter production	Primary production	Supporting
Root biomass	Primary production	Supporting
Root production	Primary production	Supporting
Seedling growth	Primary production	Supporting
Understorey biomass	Primary production	Supporting
Timber quality	Quality	Provisioning
Growth recovery	Raw materials	Provisioning
Growth resil.	Raw materials	Provisioning
Growth resis.	Raw materials	Provisioning

				Growth stability	Raw materials	Provisioning
				Log tree recruitment	Raw materials	Provisioning
				Timber prod.	Raw materials	Provisioning
				Tree biomass	Raw materials	Provisioning
Fanin et al., 2018	A	1, 2	15	soil carbon per area (concentration * bulk density)	Climate regulation	Regulating
				nematode density	Habitat provision and biodiversity	Cultural
				active microbial biomass (PLFA)	Nutrient Cycling	Supporting
				decomposition rates	Nutrient cycling	Supporting
				potential microbial activity (SIR)	Nutrient cycling	Supporting
				moss biomass	Primary production	Supporting
				root biomass	Primary production	Supporting
				shrub biomass	Primary production	Supporting
				soil exchangeable nitrogen (mixed bed ionic resin capsules)	Soil properties and fertility	Supporting
				soil exchangeable phosphorus (mixed bed ionic resin capsules)	Soil properties and fertility	Supporting
				soil mineral nitrogen	Soil properties and fertility	Supporting
				soil mineral phosphorus	Soil properties and fertility	Supporting

				soil nitrogen per area (concentration * bulk density)	Soil properties and fertility	Supporting
				soil organic matter alkyl:O-alkyl ratio	Soil properties and fertility	Supporting
				soil phosphorus per area (concentration * bulk density)	Soil properties and fertility	Supporting
Allan et al., 2015	A	2	14	total flower cover	Aesthetic values	Cultural
				soil organic C	Climate regulation	Regulating
				lack of pathogen infection	Disease and pest control	Regulating
				natural enemy abundance	Disease and pest regulation	Regulating
				bird diversity	Habitat provision and biodiversity	Cultural
				mycorrhisation	Nutrient cycling	Supporting
				phosphorus retention index	Nutrient cycling	Supporting
				potential nitrification	Nutrient cycling	Supporting
				root decomposition	Nutrient cycling	Supporting
				total pollinators	Pollination	Regulating
				root biomass	Primary production	Supporting
				shoot biomass	Primary production	Supporting
				forage quality	Quality	Provisioning

				soil aggregation	Soil properties and fertility	Supporting
Blank et al., 2014	B	4	2	breeding bird community assemblages	Habitat provision and biodiversity	Cultural
				biomass yields	Primary production	Supporting
Bradford et al., 2014	A	1, 2	5	net primary productivity	Food production	Supporting
				respiration	Nutrient cycling	Supporting
				returned litter decomposition	Nutrient cycling	Supporting
				standard litter decomposition	Nutrient cycling	Supporting
				net ecosystem productivity	Primary production	Supporting
Byrnes et al., 2014	A	1, 2, 4	5	cotton decomposition	Nutrient cycling	Supporting
				aboveground biomass	Primary production	Supporting
				belowground biomass	Primary production	Supporting
				plant N	Quality	Provisioning
				soil N	Soil properties and fertility	Supporting
Dooley et al., 2015	A	4	3	aboveground grass biomass	Primary production	Supporting
				aboveground weed biomass	Primary production	Supporting

				Nitrogen yield	Quality	Provisioning
Hautier et al. 2018	A	1, 2	8	invasion resistance	Disease and pest control	Regulating
				litter decomposition	Nutrient cycling	Supporting
				resource capture above ground (light interception) - ratio between PAR radiation above canopy and close to ground	Photosynthesis	Supporting
				aboveground live biomass	Primary production	Supporting
				extractable soil phosphorus	Soil properties and fertility	Supporting
				extractable soil potassium	Soil properties and fertility	Supporting
				resource pools below ground (percentage total soil nitrogen)	Soil properties and fertility	Supporting
Hector and Bagchi, 2007	A	4	7	decomposition	Nutrient cycling	Supporting
				% of transmitted photosynthetically active radiation (PAR) at ground level	Photosynthesis	Supporting
				above-ground (shoot) biomass	Primary production	Supporting
				below-ground (root) biomass	Primary production	Supporting
				total nitrogen pools in above-ground vegetation	Quality	Provisioning
				soil nitrate	Soil properties and fertility	Supporting
				soil ammonium	Soil properties and fertility	Supporting
Jing et al., 2015	A	1	8	soil organic C	Climate regulation	Regulating

				aboveground biomass	Primary production	Supporting
				root biomass	Primary production	Supporting
				plant N	Quality	Provisioning
				plant P	Quality	Provisioning
				soil available N	Soil properties and fertility	Supporting
				soil N	Soil properties and fertility	Supporting
				soil P	Soil properties and fertility	Supporting
Li et al., 2016	A	1	12	soil organic C	Climate regulation	Regulating
				cation exchange capacity	Nutrient cycling	Supporting
				capillary moisture		
				capillary porosity		
				pH		
				soil moisture		
				bulk density	Soil formation	Supporting
				available N	Soil properties and fertility	Supporting
				available P	Soil properties and fertility	Supporting
				total N	Soil properties and fertility	Supporting
				total P	Soil properties and fertility	Supporting

Lopez-i-Gelats et al., 2015	B	4	10	Flowering period	Aesthetic values	Cultural
				length of flowering period	Aesthetic values	Cultural
				Distinctive species	Habitat provision and biodiversity	Cultural
				species density	Habitat provision and biodiversity	Cultural
				species richness	Habitat provision and biodiversity	Cultural
				biomass production	Primary production	Supporting
				Max canopy height	Primary production	Supporting
				plant height	Primary production	Supporting
				Chorology	Quality	Provisioning
				pastoral index (i.e. fodder quality)	Quality	Provisioning
Manning et al., 2017	A	2	4	soil fauna feeding activity	Disease and pest regulation	Regulating
				beetle survival	Habitat provision and biodiversity	Cultural
				dung removal	Nutrient cycling	Supporting
				primary productivity	Primary production	Supporting
				reduction of soil compaction	Soil properties and fertility	Supporting
Maseyk et al., 2017	B	4	6	food	Food production	Provisioning

				maintenance of species of conservation concern	Habitat provision and biodiversity	Cultural
				medicinal resources	Medicinal resources	Provisioning
				N fixation	Nutrient cycling	Supporting
				raw materials	Primary production	Supporting
				sense of place	Spiritual and religious values	Cultural
Meyer et al., 2018	A	3	82	13C in soil samples	Climate regulation	Regulating
				C concentration in fine roots	Climate regulation	Regulating
				percentage of C in biomass of target plant community	Climate regulation	Regulating
				mean of herbivory in percent	Disease and pest regulation	Regulating
				mortality of trap nesting Hymenoptera	Disease and pest regulation	Regulating
				parasitism rate of trap nesting Hymenoptera	Disease and pest regulation	Regulating
				abundance of aphidina	Habitat provision and biodiversity	Cultural
				abundance of auchenorrhyncha	Habitat provision and biodiversity	Cultural
				abundance of chilopoda	Habitat provision and biodiversity	Cultural
				abundance of collembola	Habitat provision and biodiversity	Cultural
				abundance of dermaptera	Habitat provision and biodiversity	Cultural

abundance of diplopoda	Habitat provision and biodiversity	Cultural
abundance of diptera	Habitat provision and biodiversity	Cultural
abundance of enchytaeidae	Habitat provision and biodiversity	Cultural
abundance of endogeic earthworms	Habitat provision and biodiversity	Cultural
abundance of gamasida	Habitat provision and biodiversity	Cultural
abundance of gastropoda	Habitat provision and biodiversity	Cultural
abundance of heteroptera	Habitat provision and biodiversity	Cultural
abundance of hymenoptera	Habitat provision and biodiversity	Cultural
abundance of insect larvae	Habitat provision and biodiversity	Cultural
abundance of isopoda	Habitat provision and biodiversity	Cultural
abundance of lumbricus terrestris	Habitat provision and biodiversity	Cultural
abundance of mites	Habitat provision and biodiversity	Cultural
abundance of phytophagous beetles	Habitat provision and biodiversity	Cultural
abundance of phytophagous insect larvae	Habitat provision and biodiversity	Cultural
abundance of predatory beetle larvae	Habitat provision and biodiversity	Cultural
abundance of predatory beetles	Habitat provision and biodiversity	Cultural

abundance of spiders	Habitat provision and biodiversity	Cultur al
abundance of sucking herbivores	Habitat provision and biodiversity	Cultur al
abundance of thysanoptera	Habitat provision and biodiversity	Cultur al
number of burrowing holes by voles	Habitat provision and biodiversity	Cultur al
number of viable seeds of target species in the seed bank per meter square	Habitat provision and biodiversity	Cultur al
number of viable seeds of weed species in the seed bank per meter square	Habitat provision and biodiversity	Cultur al
species richness hymenoptera	Habitat provision and biodiversity	Cultur al
species richness of flower visitors per 6 minutes	Habitat provision and biodiversity	Cultur al
species richness of parasites of Hymenoptera	Habitat provision and biodiversity	Cultur al
species richness of seed bank of target plant species	Habitat provision and biodiversity	Cultur al
species richness of seed bank of weed plant species	Habitat provision and biodiversity	Cultur al
species richness of seedlings of weed plant species	Habitat provision and biodiversity	Cultur al
species richness of weeds	Habitat provision and biodiversity	Cultur al
total abundance of coleoptera including all feeding guilds	Habitat provision and biodiversity	Cultur al
basal soil respiration	Nutrient cycling	Suppor ting
biomass of soil microbes	Nutrient cycling	Suppor ting

N concentration in fine roots	Nutrient cycling	Supporting
phosphate concentration in the soil after growing season	Nutrient cycling	Supporting
LAI measured 5 cm above ground	Photosynthesis	Supporting
flower visitor frequency	Pollination	Regulating
13C in biomass of target plant species	Primary production	Supporting
15N in biomass of target plant species	Primary production	Supporting
aboveground biomass of dead material	Primary production	Supporting
aboveground biomass of target plant community	Primary production	Supporting
aboveground biomass of weeds	Primary production	Supporting
biomass of coarse roots	Primary production	Supporting
biomass of fine roots	Primary production	
cover of bare ground	Primary production	Supporting
cover of dead plant material	Primary production	Supporting
cover of target plant species	Primary production	Supporting
cover of weeds	Primary production	Supporting
growth of root length between Sept and July	Primary production	Supporting

mean diameter of roots	Primary production	Suppor ting
mean of sown plant community plant height	Primary production	Suppor ting
mean of weed plant height	Primary production	Suppor ting
number of target plant modules per meter square	Primary production	Suppor ting
number of target plant seedlings per meter square	Primary production	Suppor ting
number of weed plant seedlings per meter square	Primary production	Suppor ting
volume of coarse root standing stock	Primary production	Suppor ting
volume of fine root standing stock	Primary production	Suppor ting
percent nitrogen in biomass of sown plant species	Quality	Provisi oning
15N in soil samples	Soil properties and fertility	Suppor ting
ammonium concentration in the soil after the growing season	Soil properties and fertility	Suppor ting
ammonium concentration in the soil before the growing season	Soil properties and fertility	Suppor ting
concentration of inorganic C in solid phase soil samples	Soil properties and fertility	Suppor ting
concentration of mineral N in solid phase soil samples	Soil properties and fertility	Suppor ting
concentration of organic C in solid phase soil samples	Soil properties and fertility	Suppor ting
nitrate concentration in the soil after the growing season	Soil properties and fertility	Suppor ting

				nitrate concentration in the soil before the growing season	Soil properties and fertility	Supporting
				bulk density soil	Soil properties and fertility	Supporting
				number of weeded individuals		
				soil pH in CaCl		
				soil pH in H2O		
				soil water content per mass		
Mouillot et al., 2011	A	1	4	cotton decomposition	Nutrient cycling	Supporting
				Litter decomposition	Nutrient cycling	Supporting
				producitivty	Primary production	Supporting
				N content of aboveground biomass	Quality	Provisioning
Pan et al., 2016	B	4	5	net ecosystem C exchange	Climate regulation	Regulating
				gross ecosystem productivity	Food production	Provisioning
				ecosystem respiration	Nutrient cycling	Supporting
				soil nitrate use	Nutrient cycling	Supporting
				biomass production	Primary production	Supporting
Pasari et al., 2013	A	1	8	change in soil C	Climate regulation	Regulating
				invasion resistance	Disease and pest control	Regulating
				insect abundance	Habitat provision and biodiversity	Cultural

				insect species richness	Habitat provision and biodiversity	Cultural
				nitrogen retention in soil	Nutrient cycling	Supporting
				aboveground net primary productivity	Primary production	Supporting
				root biomass	Primary production	Supporting
				change in plant N	Quality	Provisioning
Phoenix et al., 2008	B	4	4	aboveground biomass	Primary production	Supporting
				N in biomass	Quality	Provisioning
				ammonium leaching	Water purification	Regulating
				nitrate leaching	Water purification	Regulating
Quero et al., 2013	A	1	10	organic C	Climate regulation	Regulating
				activity of b-glucosidase	Nutrient Cycling	Supporting
				amino acids	Nutrient cycling	Supporting
				hexoses	Nutrient cycling	Supporting
				pentoses	Nutrient cycling	Supporting
				phosphatase activity	Nutrient cycling	Supporting
				proteins	Nutrient cycling	Supporting

				available inorganic P	Soil properties and fertility	Supporting
				total available N	Soil properties and fertility	Supporting
				total N	Soil properties and fertility	Supporting
Soliveres et al., 2014	A	1	14	organic C	Climate regulation	Regulating
				amino acids	Nutrient cycling	Supporting
				aromatic compound	Nutrient cycling	Supporting
				hexoses	Nutrient cycling	Supporting
				pentoses	Nutrient cycling	Supporting
				phenols	Nutrient cycling	Supporting
				phosphatase activity	Nutrient cycling	Supporting
				potential N transfer	Nutrient cycling	Supporting
				proteins	Nutrient cycling	Supporting
				ß-glucosidase	Nutrient cycling	Supporting
				ammonium	Soil properties and fertility	Supporting
				available inorganic P	Soil properties and fertility	Supporting
				nitrate	Soil properties and fertility	Supporting

				total N	Soil properties and fertility	Supporting
Soliveres et al., 2016a	A	1	14	flower cover	Aesthetic values	Cultural
				soil organic C	Climate regulation	Regulating
				aboveground pest control	Disease and pest regulatiom	Regulating
				resistance to aboveground pathogens	Disease and pest regulation	Regulating
				bird diversity	Habitat provision and biodiversity	Cultural
				AMF root colonization	Nutrient cycling	Supporting
				potential nitrification	Nutrient cycling	Supporting
				root decomposition rate	Nutrient cycling	Supporting
				soil P retention	Nutrient cycling	Supporting
				pollinator abundance	Pollination	Regulating
				aboveground biomass	Primary production	Supporting
				belowground biomass	Primary production	Supporting
				forage quality	Quality	Provisioning
				soil aggregate stability	Soil properties and fertility	Supporting
Soliveres et al., 2016b	A	1	14	recreation benefits of flower cover	Aesthetic values	Cultural

				soil C levels	Climate regulation	Regulating
				pest control	Disease and pest regulation	Regulating
				resistance to pathogens	Disease and pest regulation	Regulating
				fodder production	Food production	Provisioning
				bird diversity	Habitat provision and biodiversity	Cultural
				mycorrhizal colonization	Nutrient cycling	Supporting
				phosphorus retention	Nutrient cycling	Supporting
				potential nitrification	Nutrient cycling	Supporting
				root decomposition rate	Nutrient cycling	Supporting
				pollinator abundance	Pollination	Regulating
				root biomass	Primary production	Supporting
				fodder quality	Quality	Provisioning
				soil aggregate stability	Soil properties and fertility	Supporting
Thompson and Kao-Kniffin, 2016	B	4	3	soil microbiota diversity (bacterial and fungal)	Habitat provision and biodiversity	Cultural
				plant production	Primary production	Supporting
				N leaching	Water purification	Regulating

Waag et al., 2014	A	1	8	Carbon sequestration	Climate regulation	Regulating
				N2O production	Climate regulation	Regulating
				Litter decomposition	Nutrient cycling	Supporting
				N turnover	Nutrient cycling	Regulating
				Leachate NH4	Water purification	Regulating
				Leachate NO3	Water purification	Regulating
				Leachate PO4	Water purification	Regulating
				Leachate total P	Water purification	Regulating
Pan et al., 2017	A	2	8	soil organic matter	Climate regulation	Regulating
				root density	Nutrient cycling	Supporting
				aboveground biomass	Primary production	Supporting
				plant height	Primary production	Supporting
				vegetation cover	Primary production	Supporting
				aboveground palatability	Quality	Provisioning
				soil water holding capacity	Soil properties and fertility	Supporting
				total soil N	Soil properties and fertility	Supporting

Zavaleta et al., 2010	A	1	8	change in soil C	Climate regulation	Regulating
				invasion resistance	Disease and pest control	Regulating
				insect species abundance	Habitat provision and biodiversity	Cultural
				insect species richness	Habitat provision and biodiversity	Cultural
				nitrogen retention in soil	Nutrient cycling	Supporting
				aboveground net primary productivity	Primary production	Supporting
				root biomass	Primary production	Supporting
				plant N	Quality	Provisioning
Bastida et al., 2016	A	1	5	b-glucosidase activity	Nutrient cycling	Supporting
				microbial biomass	Nutrient cycling	Supporting
				phosphatase activity	Nutrient cycling	Supporting
				soil respiration	Nutrient cycling	Supporting
				urease activity	Nutrient cycling	Supporting
Maestre et al., 2012c	A	1, 2	8	soil organic C	Climate regulation	Regulating
				b-glucosidase	Nutrient cycling	Supporting
				N fixation activity	Nutrient cycling	Supporting

				phosphatase	Nutrient cycling	Supporting
				urease	Nutrient cycling	Supporting
				ammonium availability	Soil properties and fertility	Supporting
				nitrate availability	Soil properties and fertility	Supporting
				total N	Soil properties and fertility	Supporting
Robroek et al., 2017	A	1	4	gross CO2 exchange	Climate regulation	Regulating
				methane flux	Climate regulation	Regulating
				net CO2 exchange	Climate regulation	Regulating
				dissolved organic C content	Soil properties and fertility	Supporting

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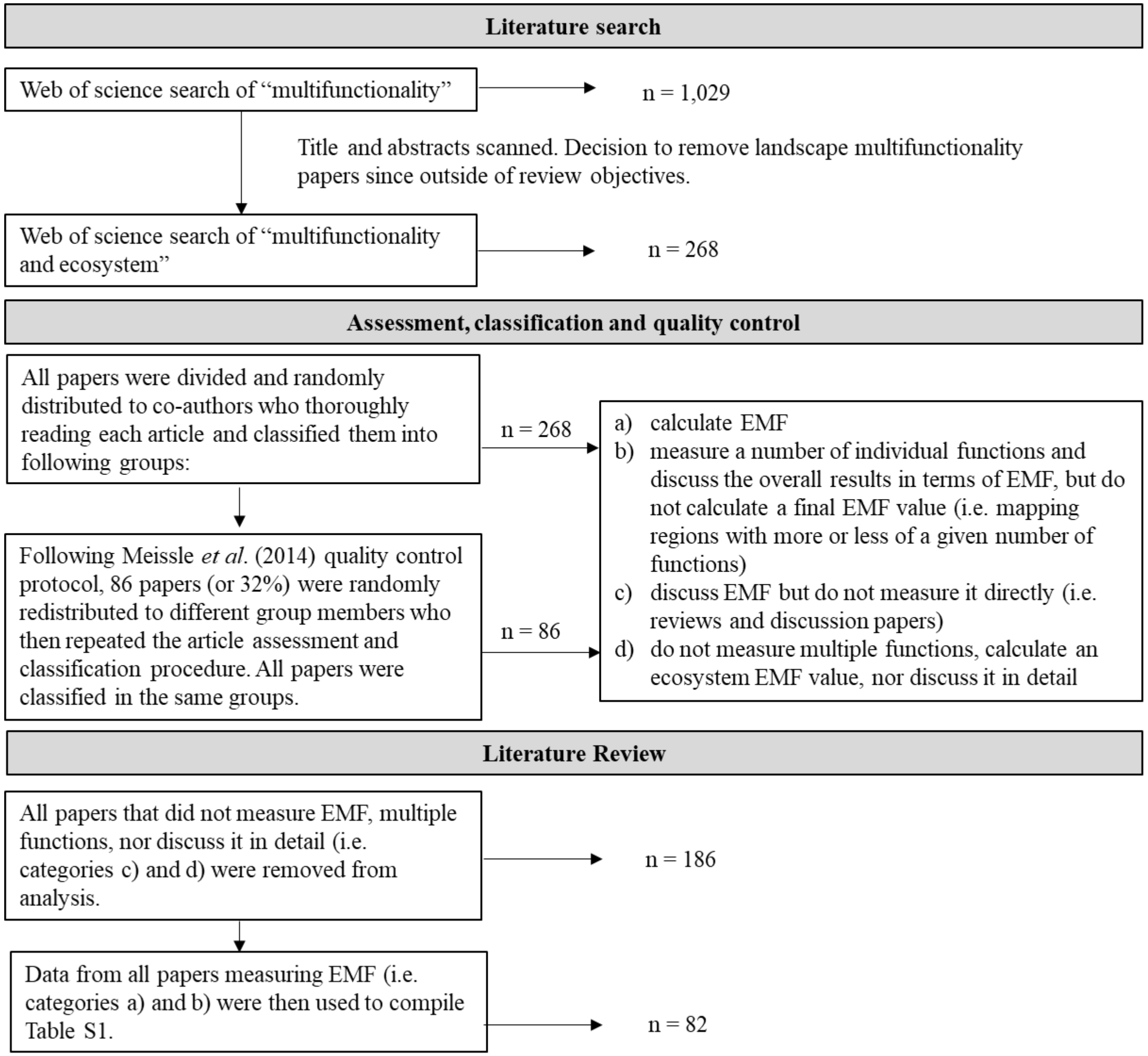
Table S2: Number of functions measured in each ecosystem function category for each land-use type.

Ecosystem service category	Ecosystem services/ Functional categories	Agroecosystems	Drylands	Forest	Grassland	Other
Cultural	Aesthetic values	3		1	5	
	Habitat provision and biodiversity	7		25	49	
	Mental and physical health	5				
	Recreation and ecotourism	4		2		
	Spiritual and religious values	1			1	
Provisioning	Food production	26		6	2	
	Raw materials	3		37		
	Quality	3		3	16	
	Medicinal resources				1	
	Fresh water	1				
	Employment	5				
	Income	10		2		
Regulating	Air quality regulation	2				
	Climate regulation	17	14	16	18	4
	Water regulation	6	3			
	Erosion regulation	8	1	2		

	Water purification	10	1	2	7	
	Disease and pest regulation	8		13	14	
	Pollination	2			4	
	Moderation of extreme events	2		9		
Supporting	Primary production	1	1	26	55	
	Nutrient cycling	31	75	36	51	9
	Soil properties and fertility	10	42	9	37	4
	Photosynthesis			1	4	

Figure S1: Conceptual diagram of literature review process.


Literature search
Web of science search of "multifunctionality"
n = 1,029
Title and abstracts scanned. Decision to remove landscape multifunctionality papers since outside of review objectives.
Web of science search of "multifunctionality and ecosystem"
n = 268
Assessment, classification and quality control
All papers were divided and randomly distributed to co-authors who thoroughly reading each article and classified them into following groups:
n = 268
a) calculate EMF
b) measure a number of individual functions and discuss the overall results in terms of EMF, but do not calculate a final EMF value (i.e. mapping regions with more or less of a given number of functions)
c) discuss EMF but do not measure it directly (i.e. reviews and discussion papers)
d) do not measure multiple functions, calculate an ecosystem EMF value, nor discuss it in detail
Following Meissle et al. (2014) quality control protocol, 86 papers (or 32%) were randomly redistributed to different group members who then repeated the article assessment and classification procedure. All papers were classified in the same groups.
n = 86
Literature Review
All papers that did not measure EMF, multiple functions, nor discuss it in detail (i.e. categories c) and d) were removed from analysis.
n = 186
Data from all papers measuring EMF (i.e. categories a) and b) were then used to compile Table S1.
n = 82